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ABSTRACT

Internet-based USGS's interactive deaggregation of probabilistic seismic hazard was used to identify principal sources of earthquake hazard at two dam sites in western Oregon. The dams are located in the western margin of the Pacific Northwest region of the United States where Cascadia Subduction Zone and shallow gridded crustal earthquakes are dominant sources of earthquake hazard. For each source, the magnitude, distance, and number of standard deviations (ε) were determined to develop target acceleration response spectra using ground motion prediction equations.

The selection of ε for the gridded crustal earthquakes was different for the two sites; one site is in an area of low to medium seismicity, while the other is in a more seismically active region. Based on the number, distances, and densities of epicenters of historical earthquakes relative to each site, the first site was given an ε of 0 while the second site was given an ε of 1.

Once the target response spectra were developed, the selection of ground motion records was performed using standard procedures.

INTRODUCTION

The specification of design ground motion parameters is one of the most difficult and most important problems in geotechnical earthquake engineering (Kramer 1996). With that in mind, we present a case history of ground motion selection for proposed dynamic analyses of dams at two sites in western Oregon.

The two dam sites, referred to in this paper as Site A and Site B, are located in west-central and northwest parts of Oregon, respectively (Fig. 1). Dynamic analyses of the dams at these two sites are proposed in the near future, and ground motion parameters and records to be used in the analyses were requested by the dam owners.

In this paper, we first outline the procedures that we used to select ground motion records. We then present the results for Sites A and B.

PROCEDURES

The goal of selecting ground motion records (time histories) is to closely match those that are reasonably expected to occur in the future. Ground motions that a specific site may be subjected to in the future can come from various earthquake sources. It is the role of seismic hazard analyses to identify these potential sources. Each source with a magnitude M at a distance R will cause ground motion at the site as a result of shear waves propagating from the source to the site. The resulting ground motion will have some distribution, which is expressed by the median and standard deviation. The number of standard deviations (ε) relative to the median needs to be determined using some criteria. Once M, R, and ε are selected, ground motion prediction equations (GMPE, also known as attenuation relationships) provide spectral accelerations.

We followed general guidelines on the seismic hazard analyses and time history selection, which are given in references such as Stewart et al. (2001), McGuire (2004), and Idriss and Archuleta (2007). The only area for which we could not find clear guidelines was the selection of ε as discussed below. The procedures we used are summarized as follows.

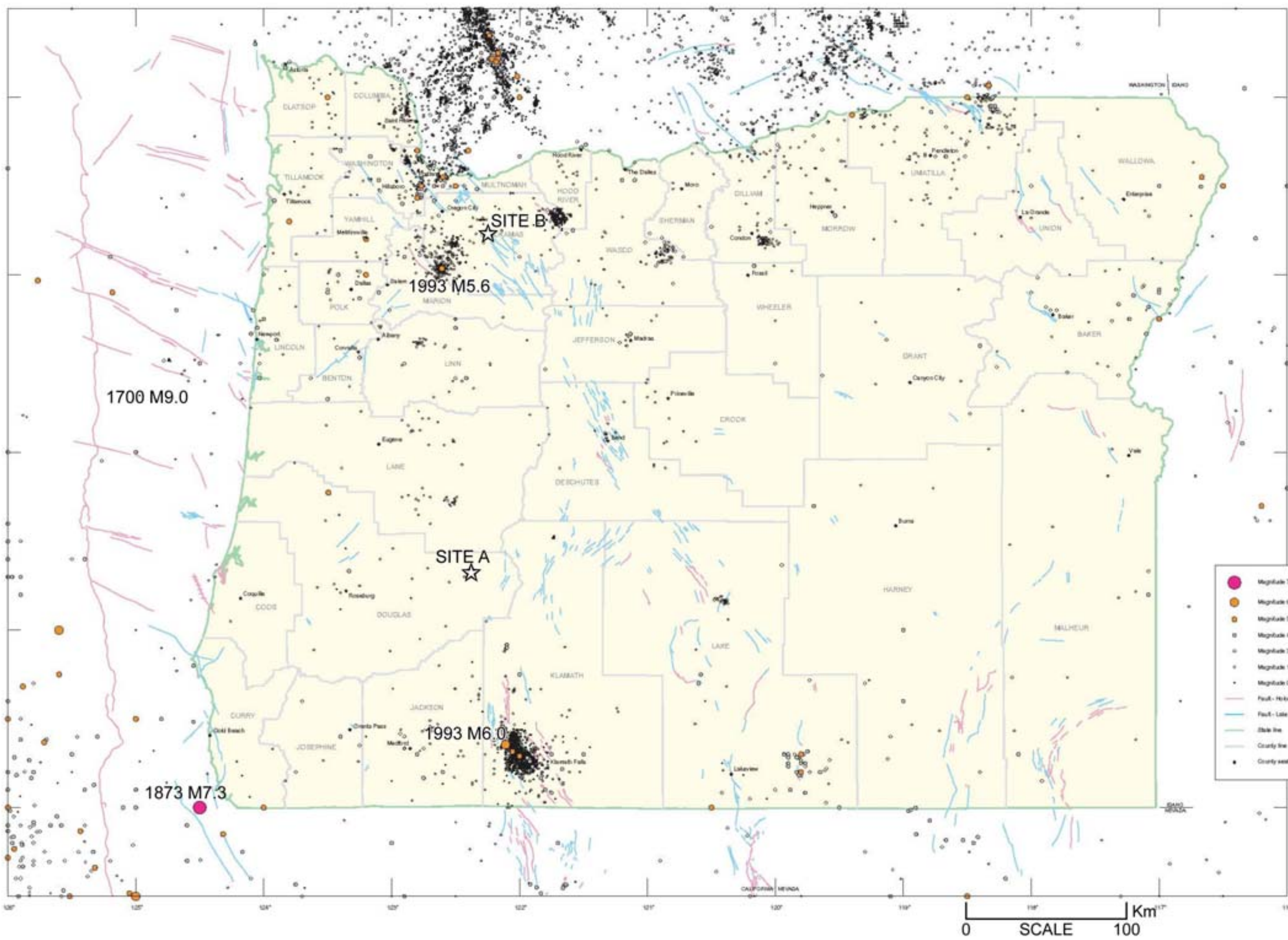

Fig. 1. Locations of Dam Sites and Historical Earthquakes in Oregon (from Niewendorp and Neuhaus 2003)

<u>Seismic Hazard Analysis</u>

Seismic hazard analyses (SHA) determine annual frequencies, levels, and sources of ground motions from future earthquakes. Information used to perform SHA consists of: historical earthquakes, geological evidence of faults, plate tectonics, and global analogy. The U.S. Geological Survey (USGS) compiles the results of SHA across the U.S. into National Seismic Hazard Maps (NSHM) and updates them periodically. Although USGS recently published the 2008 update to NSHM, we used the 2002 NSHM because the transition was taking place while we were working on this case history.

Figure 1, which is from Niewendorp and Neuhaus 2003, shows locations of known historical earthquakes during the period 1841 through 2002. It also shows locations of Holocene and Quaternary faults in Oregon. A major plate tectonics feature affecting the state is the Cascadia Subduction Zone (CSZ), where the Juan de Fuca plate subducts under the North American plate. When the locked interface between the two plates slips, it causes an interface earthquake also known as a megathrust earthquake. An interface earthquake can be as high as a magnitude 9.

It is seen that higher concentrations of historical earthquakes are in the northwest corner of the state, with 10 earthquakes with magnitudes in the range of 5 to 5.9. Also, there have been high seismic activities in the south-central part of the state, near Klamath Falls. Some notable earthquakes that have impacted the state are listed below, with approximate source-to-site distances from Site A or B.

- January 26, 1700: An estimated M9 interface earthquake on CSZ off the Pacific Northwest coast [estimated distance 140 km and 130 km west of Site A and Site B, respectively].
- November 22, 1873: M7.3 earthquake near Brookings, Oregon, about 210 km southwest of Site A.
- March 25, 1993: M5.6 earthquake near Scotts Mills, Oregon, about 40 km southwest of Site B.
- September 21, 1993: M6.0 earthquake near Klamath Falls, Oregon, about 105 km south of Site A.

Based on the above, it appears that crustal and CSZ interface earthquakes are the principal sources of earthquake hazards in Oregon. We used Probabilistic Seismic Hazard Analyses (PSHA) to determine the principal sources of earthquake hazards at the two dam sites, employing the internet-based USGS's Interactive Deaggregation for the 2002 NSHM (http://eqint.cr.usgs.gov/deaggint/2002/index.php).

We used a return period of 2,475 years in the PSHA. This means that the ground motion records were selected that are representative of predominant sources for a 2,475-year seismic hazard. The selection of the 2,475-year return period was based on the fact that dams are critical structures and consequences of their failures are significant.

The Interactive Deaggregation identifies principal sources of seismic hazard. The results consist of source category, percent contribution, magnitude (M), and source-to-site distance (R) of the principal sources. Examples of source categories include faults, subduction zone megathrusts, and random seismicity sources such as shallow gridded crustal earthquakes.

Once the M, R, and source category of a principal source are selected, available ground motion prediction equations (GMPE, also known as attenuation relations or attenuation models) for the source category can be used to determine expected spectral accelerations resulting from earthquakes with similar characteristics. Before this can be done, a decision must be made on what value to use for ε, the number of standard deviations relative to the median.

Selection of ε

The state of practice is to use an ε of 0 (median, 50^{th}-percentile) or 1 (median plus one standard deviation, 84^{th}-percentile). Blake et al. (2002) indicate that for non-critical structures, many engineers have used median ground motions, whereas for critical structures, 84^{th}-percentile ground motions have been used. Idriss and Archuleta (2007) noted that typically the median values are used when the seismic source has a relatively low degree of seismicity (e.g., average slip rate less than 0.1 mm/year), and that for high slip rate sources, the 84^{th}–percentile values are used. However, criteria for selection of ε are often not explicit.

In this case history, we used the following criteria for selecting the value of ε.

- For known faults and fault zones, the mean recurrence interval of earthquakes occurring on the fault was compared to the return period used in the SHA, i.e., 2,475 years. If the mean recurrence interval is small relative to the return period, an ε of 1 (84^{th} percentile) is used. If it is about the same or greater, an ε of 0 (50^{th} percentile) is used. In other words, how many earthquakes can be expected on the fault during the 2,475-year period. If the number is several, then an ε of 1 may be appropriate.
- For random seismicity, such as USGS's shallow gridded crustal earthquakes, the seismicity of the specific site was considered in addition to the first criteria. By seismicity, we mean historical earthquakes, or lack thereof, in the vicinity of the site. For example, even when the recurrence interval of crustal earthquakes resulting from a rupture of a fault is about the same as the return period used in the SHA, if there is evidence that there are many potential faults surrounding the site, an ε of 1 may be more appropriate. If, however, historical seismicity only supports few faults in the vicinity, an ε of 0 would be used.

Development of Target Response Spectra

After M, R, and ε are selected, GMPEs for the source category can be used to develop acceleration response spectra that can be used as targets for selection of ground motion records. We used recently-developed GMPEs including those in the 2008 Update of NSHM.

CSZ Interface Earthquakes. A combination and weighting of attenuation models developed by Youngs et al. (1997), Gregor et al. (2002), and Atkinson and Boore (2003) were used to develop target response spectra for CSZ interface earthquakes. Further information regarding selection and weighting of attenuation relations used to develop target response spectra are discussed specifically for each site in the following sections.

Crustal Earthquakes. In the 2008 Update of NSHM, USGS adopted the Next Generation Attenuation (NGA) models developed under the leadership of the Pacific Earthquake Engineering Research Center (PEER). Details of the NGA models are provided in the February 2008 issue of *Earthquake Spectra*, Volume 24, Number 1, published by the Earthquake Engineering Research Institute. These attenuation models were used to develop target response spectra for each site as discussed in the following sections.

Selection of Ground Motion Records

Ground motion records were selected for each site from a number of cataloged databases including Pacific Earthquake Engineering Research Center (PEER) Strong Motion Database; the PEER/Next Generation Attenuation (NGA)

Database; and the Consortium of Organizations for Strong Motion Observation System (COSMOS) Virtual Data Center. Ground motion records were selected from a pool of those with the source category, magnitude, and source-site distance that are similar to those of the principal sources of the earthquake hazard at the site. Ground motion records whose acceleration response spectra closely matched the target response spectrum, with scaling and stretching if necessary, were selected as the final ground motions records to be used for future dynamic analyses of the dams.

GROUND MOTION SELECTION AT SITE A

Seismic Hazard Analysis

Table 1 shows the results of PSHA for Site A for a return period of 2,475 years. Table 1 shows the predominant, relatively constant contribution of about 70 to 80 percent from CSZ interface earthquakes for period range of 0 to 2 seconds. The balance of the seismic hazard comes from crustal earthquakes. Shallow gridded (random crustal) earthquakes contribute 28, 26, and 11% for periods of 0 (PGA), 0.2, and 0.5 second, respectively.

Based on the results of the seismic hazard analysis shown in Table 1, two earthquake sources were identified as principal sources of the seismic hazard for Site A; namely the CSZ interface earthquakes and shallow gridded (random crustal) earthquakes. Appropriate earthquake magnitude and distance pairs were developed for both the subduction zone and random crustal earthquakes. Table 2 shows the source distance and magnitude pairs for both random crustal and CSZ interface events. The pair of M9 at R = 140 km for the interface earthquake was based on the deaggregation results. The pair of M6 at R=10 km for the random crustal source was selected because these values have been recommended for background earthquakes in Oregon (Idriss 2004).

Table 1. Results of PSHA for Site A
(2,475-year return period)

Period (second)	Spectral Acceleration (g)	Percent Contribution	
		Shallow Gridded	CSZ Interface
PGA	0.20	28	68
0.2	0.49	26	68
0.5	0.39	11	83
1.0	0.22	<10	81
2.0	0.11	<10	77

Table 2. Earthquake Source, Magnitude and Distance

Source	Magnitude	Distance
Random Crustal	6	10 km
CSZ Interface	9	140 km

Selection of ε

The recurrence interval of the M9.0 CSZ interface earthquakes is estimated to be 500 years (Petersen et al. 2008). For the seismic hazard analysis, we used a return period of 2,475 years, which is relatively large compared to the recurrence interval. Therefore, we used an ε of 1 or the 84th percentile ground motion for the interface earthquakes.

Since the recurrence interval of crustal earthquakes in the region is estimated to be thousands of years, it is about the same or greater than the return period of 2,475 years. In addition, Fig. 1 shows that the region in the vicinity of Site A has experienced few earthquakes in historical times and appears to be an area of low to medium seismicity. Therefore, we used an ε of 0 or the median ground motion to develop the target spectrum.

Development of Target Response Spectra

CSZ Interface Earthquakes. For the CSZ interface source, attenuation relationships developed by Youngs et al. (1997), Atkinson and Boore (2003), and Gregor et al. (2002) were used to derive the target response spectrum (5% damping ratio) for the M=9 at R=140 km interface earthquake.

A weighted average of these three response spectra was used as the target spectrum, such that the weighted average of the 1.0 second period SA value was approximately equal to the 2,475-year 1.0 second period SA value in the 2008 NSHM. The results are shown graphically in Figure 2. The weights determined in this manner are as follows:

Youngs et al. (1997) – 45%
Atkinson and Boore (2003, global model) – 45%
Gregor et al. (2002) – 10%

Random Crustal Earthquakes. Three attenuation models developed as part of the PEER Next-Generation Attenuation program were used to derive the target response spectra (5% damping) for the random crustal source. The three attenuation relations used were those by Idriss (2008), Campbell and Bozorgnia (2008) and Chiou and Youngs (2008).

At Site A, the random crustal target response spectrum for the median motions for M=6 at R=10 km was determined for both normal and reverse fault types. The PGA for reverse faults using the three NGA models ranged from 0.18 to 0.20g, with an average of 0.19g. For the normal fault mechanism, the three relationships provide a PGA between 0.13 and 0.17g with an average of 0.16g. We considered the range bounded by the average response spectra for the reverse faults and normal faults when selecting ground motion records. Plotted on Figure 2 are the average response spectra for the reverse fault and normal fault mechanisms and the spectral accelerations from the 2008 USGS Uniform Hazard Response Spectrum (UHRS) for the 2,475-year return period.

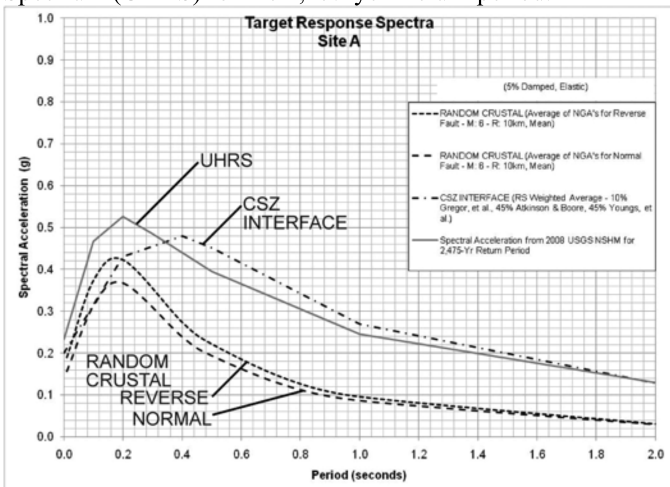

Fig. 2. Target Response Spectra and UHRS for Site A.

Selection of Ground Motion Records

CSZ Interface Earthquakes. The challenge in developing ground motions for M9.0 earthquakes is that there are no historical records of M9.0 earthquakes to date. We chose the M_S8.1 Michoacan, Mexico earthquake of September 19, 1985 and the M_S7.8 Valparaiso, Chile earthquake of March 3, 1985. We searched the database maintained by the COSMOS Virtual Data Center for ground motion records that were recorded at a rock or firm soil site with a distance from the source close to 140 km. A third motion, which is a synthetic time history developed for the analysis of a groundwater pump station in Portland, Oregon was included in the set of ground motion records.

Table 3 summarizes the ground motion records that were selected. PGAs in the table are those before scaling factors were applied. Scaling factors were applied to these ground motion records so that the SA value at 0.75 sec would closely match that of the target spectrum at the same period. Figure 3 graphically depicts the response spectra of scaled ground motions. Scaling factors so determined were 1.0, 1.5, and 1.64 for Michoacan, Valparaiso, and synthetic ground motion records, respectively.

Table 3. Ground Motion Records for CSZ Interface Earthquakes – Site A

Earthquake	Station	Magnitude	Distance	PGA
Valparaiso 3/3/1985	Santiago, Chile	7.8	122	0.12
Michoacan 9/19/1985	La Union, Mexico	8.1	84	0.16
Interface Synthetic		8.5	145	0.12

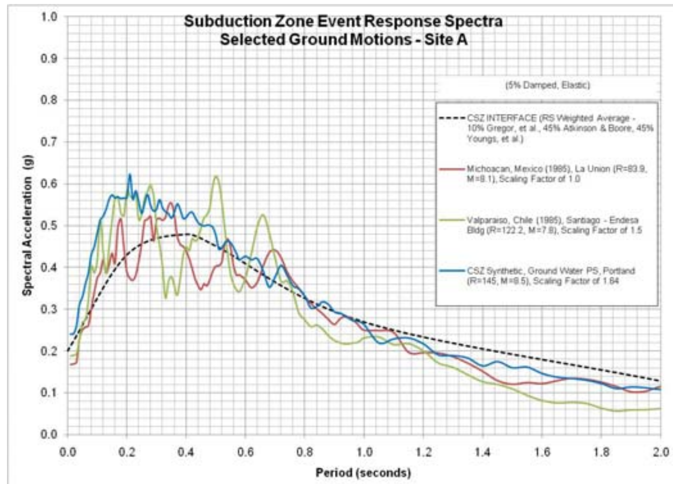

Fig. 3. Response Spectra of Selected Ground Motions for CSZ Interface Earthquakes – Site A.

Random Crustal Earthquakes. The search criteria for ground motion records for the random crustal earthquakes included: (i) M is equal to or close to 6.0, (ii) the source to site distance is equal to or close to 10 km, (iii) the recording station is on rock or stiff soil, and (iv) its response spectra matches the target shown in Figure 2. First we searched the records in PEER's NGA Database (http://peer.berkeley.edu/nga/) for those that satisfy criteria (i) through (iii). The next step was to plot the response spectrum of each of these records and compare with the target spectrum of Figure 2. Six ground motion records were selected, which are listed in Table 4. Figure 4 shows the response spectra of the 6 ground motion records plotted against the target response spectrum. Scaling was not used for these ground motion records.

Table 4. Ground Motion Records for Random Crustal Earthquakes – Site A

Earthquake	Station	Magnitude	Distance	PGA
Whittier Narrows	Brea Dam	6.0	19	0.15
Whittier Narrows	Orange Co. Res.	6.0	18	0.20
Kozani, Greece	Kozani, (L)	6.4	14	0.21
Kozani, Greece	Kozani, T	6.4	14	0.14
Helena, Montana	Carroll C. (270)	6.0	6.3	0.17
Helena, Montana	Carroll C. (180)	6.0	6.3	0.15

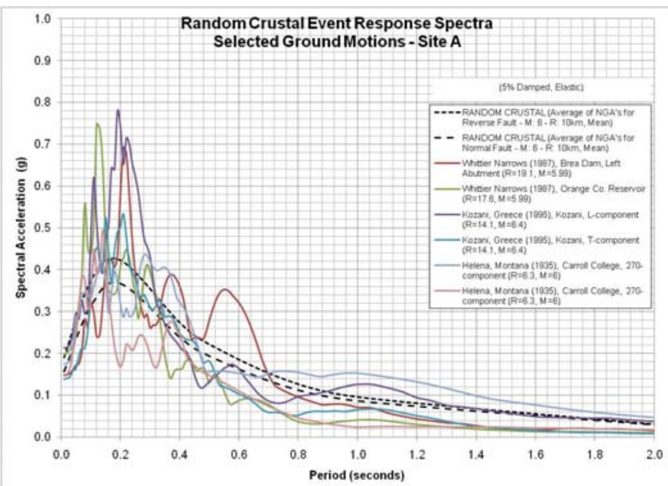

Fig. 4. Response Spectra of Selected Ground Motions for Random Crustal Earthquakes – Site A.

GROUND MOTION SELECTION AT SITE B

Seismic Hazard Analysis

Seismic hazard analyses at Site B were performed to determine contributing sources to earthquake hazard at the site. Table 5 compares the relative contribution from sources contributing to the seismic hazard for a return period of 2,475 years.

Table 5. Results of PSHA for Site B (2,475-year Return Period)

Period (second)	Spectral Acceleration (g)	Percent Contribution	
		Shallow Gridded	CSZ Interface
PGA	0.29	69	27
0.2	0.69	68	28
0.5	0.48	39	56
1.0	0.25	33	61
2.0	0.12	28	66

Table 5 indicates the Shallow Gridded (random crustal earthquakes) seismic source as the predominant contributor for the short period range (PGA to 0.2 seconds). Their contributions are 69% at PGA, but drop to 28% at 2.0 second period for the 2,475-year return period

For longer periods (0.5 to 2.0 seconds), the predominant contribution is from the CSZ interface earthquakes (Magnitude 8.3 and 9.0 combined). For the 2,475-year return period, the range is from 27% at PGA to 66% at 2.0 second period.

The balance of the seismic hazard (not shown in Table 2) comes from known crustal fault sources. Known faults with contributions greater than 1% include Grant Butte Fault, Mt. Hood Fault and the Portland Hills Fault. For the 475-year and 2,475-year return periods, the combined contributions from these faults are about 5% or less.

Based on the results of the probabilistic seismic hazard deaggregation (Table 5), two sources were identified as principal sources of seismic hazard at Site B. These were the random crustal (shallow gridded) earthquakes and Cascadia Subduction Zone interface earthquakes (Magnitude 8.3 and 9.0). Appropriate earthquake magnitude and distance pairs were developed for both the random crustal and subduction zone earthquakes based on the deaggregation. Table 6 shows the source distance and magnitude pairs for both random crustal and subduction zone events.

Table 6. Earthquake Source, Magnitude and Distance

Source	Magnitude	Distance
Random Crustal	6	10 km
CSZ Interface	9	130 km

Selection of ε

An ε of 1 was selected for the M9.0 CSZ interface earthquakes in a manner similar to Site A.

For random crustal (shallow gridded) earthquakes, an ε of 1 (84th percentile) was selected based on the fact that Site B is in a region of moderate seismicity (see Fig. 1). It was also seen that 84th-percentile ground motions for a M=6 earthquake occurring at a distance of R=10 km closely match the 2008 NSHM spectral acceleration values for the period range of 0.1 to 0.4 seconds for the return period of 2,475 years.

Development of Target Response Spectra

For CSZ interface source , attenuation relationships developed by Youngs et al. (1997), Boore-Atkinson (2003), and Gregor et al. (2002) were used to derive the target response spectrum (5% damping ratio) for the M=9.0 and R=130 km interface earthquake.

A weighted average of these three response spectra was used as the target spectrum, such that the weighted average of the 1.0 second period SA value was approximately equal to the 2,475-year 1.0 second period SA value in the 2008 NSHM. The results are shown graphically in Figure 5. The weights determined in this manner are:

Youngs et al. (1997) – 45%
Atkinson and Boore (2003, global model) – 45%
Gregor et al. (2002) – 10%

For the random crustal source, the five NGA ground motion models were used to derive the target response spectrum (5% damping ratio) for a M=6.0 and R=10 km random crustal earthquake.

At Dam Site B, the random crustal target response for the 84th percentile motions was determined for both normal and reverse fault types. The PGA for reverse faults using the five NGA models ranged from 0.24 to 0.36g, with an average of 0.30g. For the normal fault mechanism, the NGA relationships provide a PGA between 0.19 and 0.32g with an average of 0.27g. We considered the range bounded by the average response spectra for the NGA reverse faults and normal faults when selecting the time histories. Plotted on Figure 5 are the average response spectra for the reverse fault and normal fault mechanisms and the spectral accelerations from the 2008 USGS UHS for a 2,475-year return period.

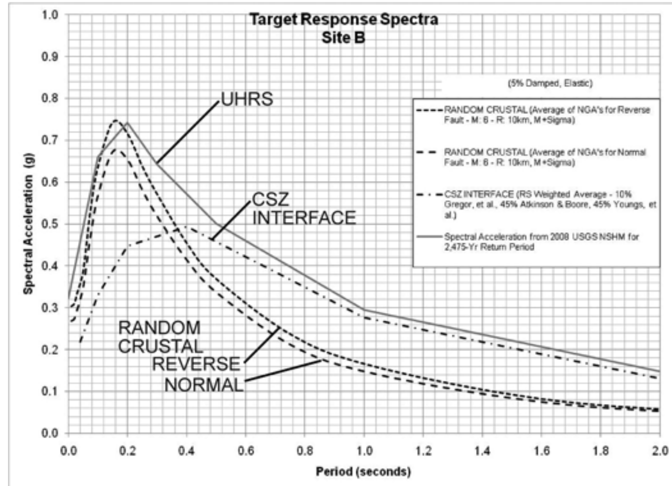

Fig. 5. Target Response Spectra and UHRS for Site B.

Selection of Ground Motion Records

CSZ Interface Earthquakes. Subduction zone ground motions were selected from earthquake records for two subduction zone events (the 1985 Michoacan, Mexico earthquake and the 1985 Valapraiso, Chile earthquakes). A third motion, which is a synthetic time history developed for an analysis of a dam site near Portland, Oregon was included in the set of ground motion records.

The horizontal earthquake response spectra (at 5% damping) were compared to the target response spectrum. The response spectra with similar characteristics were selected, scaled, and stretched in a way that spectral accelerations for the period range of interest (0.1 to 0.5 seconds) were in the range of the target response spectrum. The stretching factor was 1.25 for the three ground motion records. The scaling factors were 1.4, 1.0, 1.8 for Valparaiso, Michoacan, and synthetic ground motion records, respectively. Table 7 shows parameters of the selected earthquake ground motions. PGAs in the table are those before scaling factors were applied.

Table 7. Ground Motion Records for CSZ Interface Earthquakes – Site B

Earthquake	Station	Magnitude	Distance	PGA
Valparaiso 3/3/1985	Santiago, Chile	7.8	122	0.12
Michoacan 9/19/1985	La Union, Mexico	8.1	84	0.16
Interface Synthetic		8.5	174	0.12

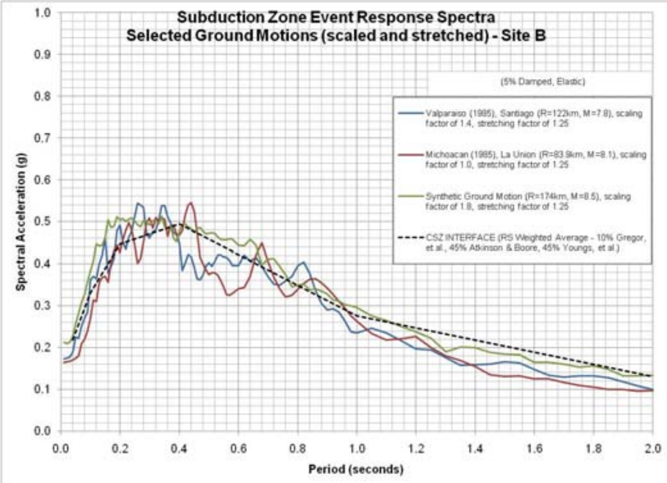

Fig. 6. Response Spectra of Selected Ground Motions for CSZ Interface Earthquakes – Site B.

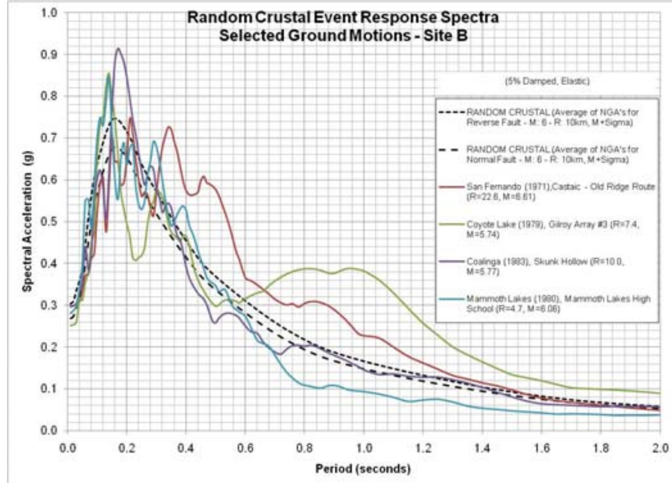

Fig. 7. Response Spectra of Selected Ground Motions for Random Crustal Earthquakes – Site B.

Random Crustal Earthquakes. The random crustal earthquake ground motions that met the magnitude, distance, and rock site criteria were further analyzed by comparing their response spectra (at 5% damping) with the target spectra shown in Figure 5. Since many records are now available, we did not attempt modifying the records by scaling or stretching. Four acceleration time histories were selected that closely matched the target response spectra, with particular emphasis in the period range from 0.1 to 0.5 seconds. Selected ground motions are shown in Table 8. The individual response spectra (geometric mean of the horizontal pair) for the selected time histories are shown on Figure 7.

Table 8 Ground Motion Records for Random Crustal Earthquakes – Site B

Earthquake	Station	Magnitude	Distance	PGA
San Fernando	Castaic – ORR	6.6	23	0.30
Coyote Lake	Gilroy Array #3	5.7	7	0.26
Coalinga	Skunk Hollow	5.8	10	0.30
Mammoth Lakes	MLHS	6.1	5	0.28

CONCLUSIONS

This paper presented case histories of ground motion record selection for two dam sites in Oregon. Principal sources of seismic hazard were determined probabilistically using USGS's Interactive Deaggregation of the National Seismic Hazard Maps. Once the principal sources were identified, target response spectra were developed deterministically using Ground Motion Prediction Equations for the source categories. Our selection of ε was based on (i) the recurrence interval of earthquakes representing the principal sources of seismic hazard, (ii) the return period used in the probabilistic seismic hazard analysis, and (iii) the seismicity of the project site.

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